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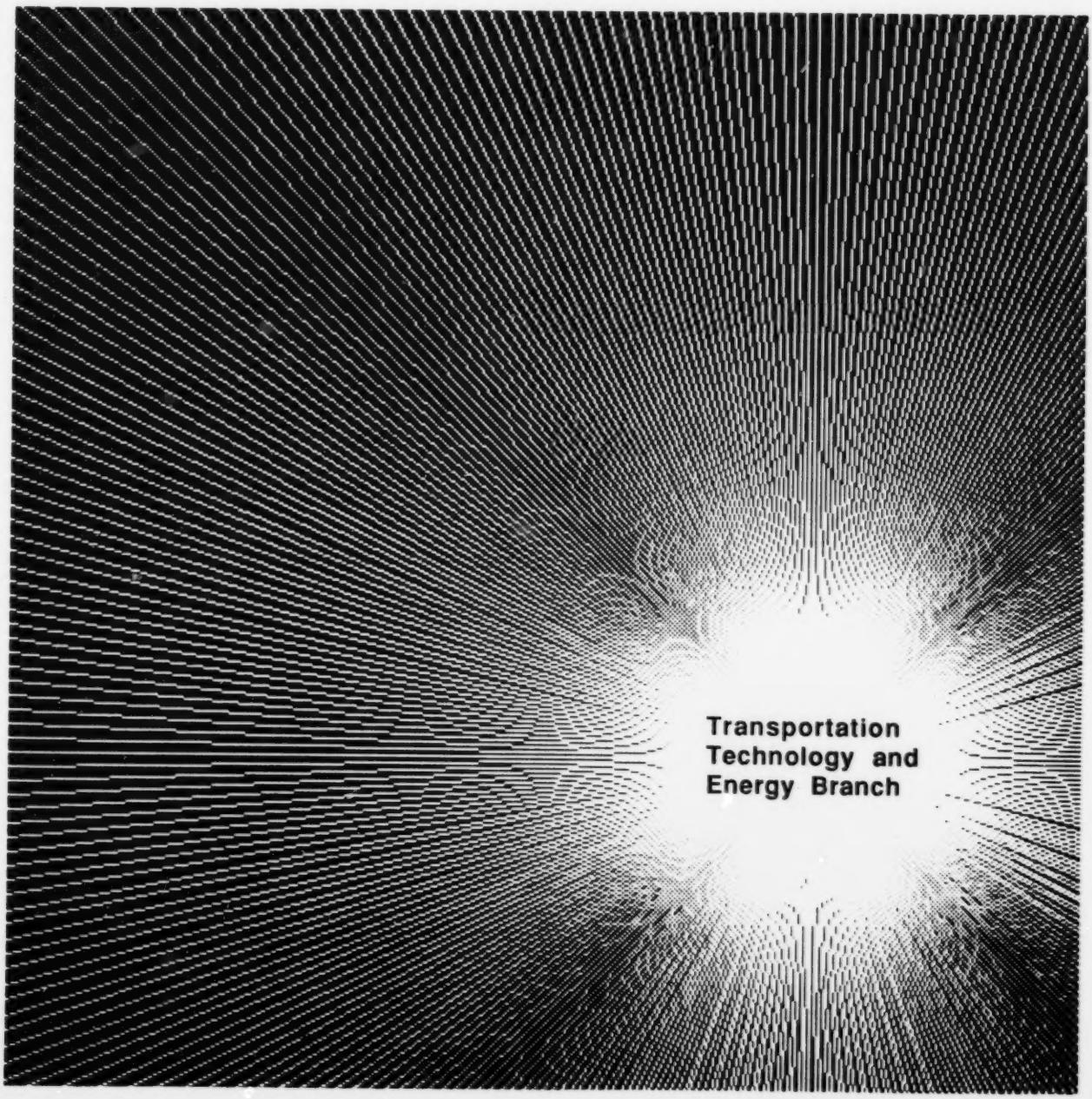

Robotic Cleaning of Toronto Transit Commission Subway Cars: A Feasibility Study

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Executive Summary

This report illustrates the feasibility of using robots to clean the undersides of Toronto Transit Commission (TTC) subway cars. Presently, this type of cleaning is done manually at the TTC in two operations: blowdown and degreasing.

During blowdown, compressed air is used to remove dry dust and dirt from the electrical components. The worker wears protective equipment and a breathing apparatus. The work is carried out over a giant vacumn cleaner inlet. Unfortunately, the dust collection is less than ideal; a good portion of the dirt spreads throughout the shop. Consequently, although the blowdown is done before the main shift reports for work, it is a source of irritation for all shop personnel.

Degreasing is an operation in which a hot water and soap solution is sprayed at the bogies, couplers, and other components to remove grease and dirt. This job is also very unpleasant and the quality of work is difficult to control.

A feasibility study of the use of robotics for these tasks was undertaken by the Ministry of Transportation of Ontario (MTO), the TTC, and Vadeko International Inc. The study concluded that three conventional painting robots travelling on 200-foot long tracks would be suitable to perform both blowdown and degreasing.

The current degreasing bay would be modified to accommodate both operations in the same location, thus containing dirt and dust. The system would be controlled and observed by one operator from a suitably air conditioned cabin equipped with remote cameras. The train would be driven into the cleaning bay and the operator would remove the covers for blowdown or cover the motor inspection windows for degreasing. The rest of the job would be completed automatically and the system itself would establish the exact position and height of the train.

An appropriate air recirculation system would control the dust during blowdown and speed up the drying of the cars following degreasing.

The benefits that are expected from the robotics system as compared to the manual operation include: better quality and consistency of cleaning; elimination of air pollution in the building; reduced fire hazard in service; increased life of equipment; cleaner vehicles that are more acceptable for inspection and maintenance crews; better utilization of the facility and manpower; and greatly improved working conditions for cleaning personnel.

1/ Introduction

This report is the result of an unsolicited proposal on July 20 1987, by Vadeko International of Mississauga, Ontario, to the Ministry of Transportation of Ontario (MTO). The proposal recommended that a study be made of the feasibility of using industrial robots to clean the undersides of Toronto Transit Commission (TTC) subway railcars.

Vadeko International Inc. is a 100% Canadian-owned, high-technology company, active in a range of industrial sectors, including aerospace, transportation, banking, and high-volume manufacturing. Its technology base includes flexible automation, large-scale robotic systems, industrial robot research, nuclear maintenance devices, space systems, and thin-film deposition.

Vadeko is noted for the design and implementation of large- and very large-scale industrial robot systems, especially for use in environments characterized by unpleasant or hazardous working conditions that have an adverse effect on the productivity and safety of human workers. Notable among these is the CN Rail's robotic paint application system (RPAS), the world's largest off-line programmed, multi-robot painting system. Installed in CN's repair and overhaul facility in Transcona, near Winnipeg, RPAS significantly decreases the time necessary to paint a hopper car, while eliminating the need to expose a human painter to an enclosed hazardous environment.

Having performed several studies in the field of railway technology, Vadeko was aware of many of the factors involved in the undercar cleaning of rail vehicles. One of them was the importance of cleaning electric systems that rely on the "third rail" power source technique. These systems are at significant risk from accidental fire, because of the accumulation of grease and dust in the proximity of electrical equipment. Thorough, periodic cleaning is essential to reduce this risk to a minimum.

Vadeko felt that a detailed study would confirm the technical feasibility of a multi-robot system to perform this maintenance regime, as well as identify the improved health and safety factors and the cost savings that could result from such a system.

2/ Undercar Cleaning for Preventive Maintenance

Throughout the various transportation authorities, the need for preventive maintenance is becoming more apparent.

Presently, the major reasons for cleaning railcar compo.ents are to prepare the vehicle for regular inspection or maintenance and to remove grease, which is a fire hazard. At the TTC, there are two types of component cleaning operations: blowdown and degreasing.

For the blowdown operation, an operator removes covers from electrical components, and then uses a wand to direct a stream of shop air, 80 - 100 psi (pounds per square inch), to blast away dirt and dust. A second operator sits in the cab and simply drives the train forward to position the railcar components to be cleaned over a large vacuum duct where the dirt and dust is to be collected by a cyclone vacuum machine. The driver is signalled to move by conventional traffic signals operated by the cleaner when each part is completed.

However, the collection equipment is not very efficient and much of the dirt and dust is free to spread around the entire carshop. Once the procedure is completed, the train is driven further down the track where regular lubrication, inspection, and maintenance is carried out.

Blowdown operations are typical in subway maintenance facilities as it is recognized that cleaning the major components makes the inspection and removal of parts more efficient and produces significant time savings due to clean equipment.

The other type of cleaning (not performed by all underground transportation authorities) is the degreasing operation, in which very high pressure water (1000 - 1500 psi) and detergent is sprayed at mechanical components to remove grease and dirt build-up.

This operation is performed mainly to remove dirt and grease from areas where there is a risk of fire, primarily in the area of the motors and brakes.

The TTC attempts to perform this operation twice yearly due to the build-up of grease from automatic greasing machines in the rail system and because the system is partly above ground rather than completely underground as many other systems are.

What is becoming more apparent from various studies is that performing regular and thorough cleaning operations on any type of equipment, such as railcars, inevitably increases the component's life span and is thus cost-effective.

One major limitation is the availability of suitable facilities to perform this type of work reliably, effectively, and frequently. Even when the manual equipment is available and the vehicles are introduced to the system, the process is so unpleasant for the operator, in spite of protective clothing, that the operation is not always performed effectively.

An automated system would allow a high throughput yet produce a very effective, thorough cleaning operation and would improve the working environment of the operator.

3/ The Use of Robotics in Industry

It is fairly well known that robots are used in a variety of industrial applications, primarily in the automotive industry. However, the full capabilities of robots are not very well appreciated, even by some trained and experienced members of the engineering and manufacturing world. Unfortunately, because the industrial robot is termed "high tech," it is often mistakenly assumed that the robot is only used in high-technology fields and applications. This misunderstanding is preventing the influx of robots into industry at the speed once thought possible and necessary for the North American marketplace to survive and expand.

Robots are merely simple machines controlled by a computer. Their primary function is to perform straightforward tasks repetitively - no more than that. The ability to reprogram them, using only software allows for a great degree of flexibility in their operation. Significant cost savings and increased productivity come about as a result of this flexibility.

Industrial robots come in many shapes and sizes and can be used to perform tasks such as:

- painting
- welding
- assembly
- machine loading/unloading.

Once taught to perform a simple task within its reach capabilities, the robot will continue to perform that task day after day very accurately and very reliably. A common mistake in industry is to attempt to make the robot perform tasks that are too difficult or that fluctuate in one form or another. The robot will only do what it has been taught and will not tolerate anything more than minor deviations in the environment around it. The trick to finding a good application for a robot is to locate a task that is highly repetitive with minimum variance.

One such application is painting. Assuming the robot is fit to be located in an explosive environment (due to solvents in the air), it can easily turn on a paint gun at the end of its arm and follow a pre-taught path to consistently paint a particular part within its reach. One major advantage of this type of application is that the distance from the paint gun to the part is not critical and, most importantly, the robot and the part never have to come in contact with each other. Therefore, a paint application is one of the simplest to set up.

One can immediately see many similarities between painting and the operations performed during the cleaning of railcars. A gun is used to spray a substance (such as paint, air, or water); the parts are very common; and, best of all, the gun never has to come in contact with the railcar.

The major disadvantages of railcar cleaning are the sheer size of the vehicle and the difficulty of positioning the railcar into a common location so that the robot(s) know where it is. A robot cannot think and, unless instructed or moved to the true location of the railcar, will attempt to clean a railcar that is not positioned correctly to receive the robot's cleaning movements.

These problems can be overcome by placing the robots on tracks that take the robot to each component and by using other mechanisms to correct the robot's starting position to suit the real railcar position.

4/ Robots in Hazardous Environments

There are two types of hazardous environments. One is an explosive atmosphere in which the equipment must be designed to ensure that the atmosphere cannot be ignited and cause an explosion. The other type is an atmosphere hazardous to humans who work in it.

Sometimes an environment can be hazardous in both ways. A painting environment, for example, is hazardous to the operator and carries the risk of explosion. The use of a robot will allow the operator to be remote from the area and special painting robots designed for these environments (Class 1 Division 1) are used to prevent explosions.

Any process that pollutes the breathing atmosphere for human operators is considered hazardous, even if the contaminants are not identified as a direct health hazard. Dirt from a cleaning operation creates such an environment. This atmosphere is really more unpleasant than hazardous, however it should still be treated with the same concern and avoided as much as possible.

5/ Similar Systems in North America

At present there are no known fully commissioned robotic applications for the undercar cleaning of subway railcars. However, the Long Island Railroad and the Montreal transit system are in the process of implementing them. Part of this study involved visits by Vadeko, MTO, and TTC personnel to these properties.

5.1/ Other Transportation Authorities

An all-electric, articulated, industrial robot is in use at the Montreal Beaugrand site. This particular installation uses large volumes of blowdown air to clean the bogie areas only. Because the bogies in the Montreal system are so complex, a highly accurate robot is needed. The electric robot fills this need and, because it doesn't perform the degreasing operation, water damage is not a concern.

In this installation, a single robot is mounted under the railcar on a track used to position the robot in one of several pre-programmed locations. The railcar is driven into the small booth area in stages, i.e., one bogie is cleaned at a time. The robot then performs a single-axis search routine in order to accurately locate the railcar bogie along the track. The robot now performs its cleaning operations with a dual spray nozzle (straight and 90 degrees). Although not subject to the strict requirements of a system necessary to clean a full railcar pair, the Montreal system still required several months of commissioning.

The robotic undercar cleaning system (RUCS) being designed for the Long Island Railroad Company (LIRR) by Vadeko International Inc. is a turnkey operation with dual robots on either side of a railcar pair, mounted on fully programmable tracks.

The LIRR system will perform operations very similar in nature to the TTC blowdown. Shop air is used to clean mainly electrical components prior to the regular 90-day inspection and maintenance program, mandatory for the New York Metropolitan Transportation Authority (MTA).

Although it is a new building, the LIRR Undercar Cleaning and Wheel Truing Facility at Hillside, New York was originally planned for manual cleaning operations. Consequently, the cleaning area incorporates raised rails only 36 inches high with very tight width and height restrictions. Due to the limited work envelope available, the LIRR facility will incorporate six-axis, all electric, articulated robots with multiple tool change systems. The common problem of railcar positioning is handled by inspecting the railcar location automatically, and by offsetting the robot positions in two co-ordinates in order to correct for railcar position on the tracks and for the inevitable wheel wear.

It is the use of a rubber tire/steel wheel combination in the Montreal subway system that eliminates the need for railcar position inspection in more than one axis (because there is no wheel wear on the auxiliary steel wheels).

5.2/ Long Island Rail Road Company

The LIRR of New York has recently let a contract for the design, building, and installation of a blowdown system at their Hillside Facility in Hollis, New York, to Vadeko International Inc. of Mississauga, Ontario, the authors of this report.

The system will include two small articulated robots mounted on linear tracks that will perform blowdown operations on twinned A&B railcars.

Although the installation is to be located in a new building, it was not designed with robotics in mind, therefore the track height is only 0.914 m (36 in). Consequently, the available selection of robots is extremely limited.

In general, the LIRR application will be similar to the system detailed in this study.

The robotic undercar cleaning system (RUCS) is a fully automatic system incorporating a master controller and two robots with their independent controllers. The two robots, located on either side of the railcar, are capable of traversing the entire distance of the cleaning area by way of a carriage mounted on linear tracks. This enables the robots to be automatically positioned anywhere along the railcar, in order to clean various undercar components.

Cleaning will involve the use of different tools mounted on the ends of the arms, passing air, as required. The manipulator is a six-axis, DC servo motor unit, with axis speeds exceeding 200 degrees per second and a repeatability of ±0.004 inches. The robot carriage, driven by a seventh servo, is capable of traversing the cleaning area in approximately one minute. Specific aspects of the system are described below.

Robot Programming

Programming of the robot is made relatively simple due to the broad level of available commands. Programs are generated through a teach pendant and consist of logic steps for sequencing, peripheral control, as well as robot movements. The programming language supports fully structured programs consisting of main programs and sub-routines. The robots are capable of operating in the following playback modes, which can be used alternately within a program:

- point-to-point
- linear interpolation
- circular interpolation

and can be used alternately within a program.

Master Controller

The master controller, an industrial computer housed in an industrial rack mount enclosure, is located in the operator's control room. This controller is linked to all vital parts of the system via discrete input and output.

The master controller is programmed using a high-level programming language in the MS-DOS environment. This gives the system excellent programming flexibility and logic structuring.

One of the major tasks performed by the master is the inspection of railcar components. This inspection, which determines the location and height of the car, involves high-speed processing, and when satisfied, sends a signal to the robot controller for offset vectoring.

General System Description

The robotic undercar cleaning system (RUCS) consists of two major areas:

- cleaning area
- control room

The cleaning area consists of the following major sub-systems:

- robots
- carriage
- tracks

RUCS interfaces with one other system in the cleaning/lubrication area – the car progression system.

The progression system incorporates a programmable logic controller (PLC) for its control and it is through several discrete inputs and outputs that the master controller and progression system are interlocked.

In the event that either system "goes down," the operator's panel has a keyswitch to allow the operator to signal that the interlocking signals should be ignored. This allows continuing operation of the system that is still up, however operator awareness must be heightened to ensure safe operating practices are in place.

Once a railcar is in position the operator can start the RUCS and be prompted at the main screen as to which of several options are required.

When automatic cleaning is selected and the "start" initiated, the system will prompt the operator for the eight-digit railcar number. If

the number is correct, the system will perform diagnostic checks on the robot system to ensure that it is ready to begin operation.

If at the beginning, a power-up was performed (cold start), the robot bases are checked for correct positioning and the robots then perform their calibration or homing routines. This will send the robots to their home locations at either ends of the tracks.

As the true railcar position is unknown (± 3 inches), it is necessary for the robots to establish the railcar's true position along the track and also to establish the bogie and bodywork heights which can vary due to wheel wear. This process is called "railcar inspection" and is performed by the robots.

By recording the distance moved during the search routine, the robot can now use its relative functions in order to offset all cleaning programs by the relative offset detected. This routine will allow the robots to accurately work on any component on the railcar that is in a truly representative location (as per the railcar manufacturer's design).

Any unusual or misplaced components could cause a problem for the robots if they are located in the path of a taught program. To deal with these occasions, the robot incorporates a device that deflects when an overload on the tool is detected and places the robot in an emergency stop condition.

The robot now moves along the track to the first cleaning location which is a taught position, plus the established lateral offset generated by the inspection routine. The robot is in the start position during this move.

Once at the cleaning position, the robot picks up a cleaning tool and manoeuvres under and along the railcar, cleaning all areas accessible with that tool within an acceptable range.

Once the railcar cleaning is complete, the progression system will "inch" forward approximately 12 inches, which will rotate the four

commutators, and the robots will return along the railcar, cleaning each commutator using the four original offsets used to locate each bogie.

The cleaning is now complete and if the operator had selected aisle cleaning, the robots will automatically clean the rail track, the robot track, the carriage, the robot itself, and the aisle area.

Upon full completion, a warning light will signal the operator that the robots have stopped and that the railcar can be moved into the lubrication area.

The control room is located on the platform, midway along the length of the cleaning area. The room houses the major control equipment.

Cleaning Area

The cleaning area is the area under the platform between the end walls and access doors. It is divided into three areas:

north aisle
south aisle
centre aisle

The north and south aisles contain the robot and track sub-systems, while the centre aisle is clear for manual inspection, etc. Each cleaning aisle has a twin track running its entire length.

Mounted on tracks is a carriage, which supports a robot.

Robots

The robots are six-axis, articulated, industrial robots, incorporating the standard six axes and an optional seventh axis for the track. The robot is an all-electric, full-servo system. Despite its compact size, it is a light- to medium-duty robot.

The robot was chosen for this application for its compact size, reach, manoeuvrability, speed, and repeatability.

The construction of the robot includes suitable protection to prevent water ingress into its electrical components, such as its motors.

The robot incorporates both tachometers for speed control and optical encoders for position control. Each encoder has a gross home position enabling the system to calibrate itself without the use of external signals such as microswitches (incremental encoders). However this type of control system loses its home reference during a power down. Consequently, the robot must perform a calibration sequence upon a cold start. This sequence involves each axis moving until the home pulse of the encoder is located. This sets the robot's home position and all moves are referenced from that point, resulting in a highly repeatable operating system.

During a normal start-up procedure, the robot movements will be very small and the process will occur quickly. Only if the system is shut down fully with the robots along the track will the calibration need to be closely monitored by operator via closed circuit TV.

Carriage
Mounted on the tracks is a carriage. On the carriage is carried the robot, tool racks, seventh axis motor drive and junction boxes.

Tracks
The robot tracks are assemblies consisting of the main supporting beam structure, linear ways, gear rack, and mounting feet.

5.3/ Montreal Transit System

Our information on the Montreal system is limited, however, we do know that the system incorporates only one robot mounted on a short track that blows down the accumulated rubber dust as the railcar enters the facility. It is not designed for degreasing and, in its present form, it has some problems with airborne contaminants and high noise levels.

Early in 1988, the Montreal transit subway system installed a robotic undercar cleaning system in the Beaugrand repair station. The system was designed and built by CRIQ, the Quebec governmental organization for high technology. The system underwent many modifications before it was ready for daily operation by Montreal transit staff.

The Montreal transit vehicles incorporate rubber tires for the normal ride, however inboard of the tires are normal steel wheels as found on all railway vehicles. Used only for emergency and additional braking and in workshops etc., the steel wheels wear very little, therefore no allowance is necessary for a variation in wheel diameter.

Because of the rubber tires, the steel wheels ride a minimum of one inch above the tracks. The rails in the shop are elevated so that the steel wheels ride on them. This eliminates the need for robot height adjustment due to varying bogie heights in conventional steel wheel systems.

The basic system consists of an ASEA industrial, all-electric, articulated robot mounted on a track. The assembly is located in a pit under the railcar, beneath the tracks (central). The robot is controlled by its own controller incorporating the maximum memory capacity available.

Overall control and control of the track itself is handled by a small programmable logic controller (PLC). The track incorporates stepper motors and positioning is consequently crude, but effective for this particular application.

The purpose of the system is to blowdown with compressed air the forward and rear bogies only. As the subway system is totally underground, the need for washing occurs only once every five years. The majority of the residue to be cleaned is rubber tire dust and leaking lubricant.

The bogies are extremely complex and many "teach" points are required in order to clean them sufficiently.

The ASEA robot was selected partly because ASEA was willing to co-operate extensively with Montreal in the early stages and loaned CRIQ a robot for the preliminary testing.

Small gaps in the bogie necessitates the use of a highly accurate robot.

Before the operation begins, the operator must ensure that pipes and hoses that can obstruct the robot are clear in the bogie area. The railcar is then driven into a small booth within the main building and is directed by traffic lights.

As the railcar enters the booth, external fixed nozzles turn on to clean the outside edges of the railcar.

Red signals the driver that he is not in position and to move forward; amber indicates that the car is within three feet of the target; and green means within 11 inches of target and therefore stop!

When the railcar is in position, as detected by sensors aimed at the wheels, the driver leaves the cab and the systems are started.

The robot moves up to a bogie and uses a sensor to detect the longitudinal position of this bogie. This gives it sufficient information and, although measured in only one direction, it is enough for the robot to offset its starting position on the track.

The track is calibrated (set to zero) and moves the robot to the first position for cleaning.

After each sub-program, the PLC moves the robot via the track to the reset location to clean more of the bogie. The cleaning system is deactivated during track movement.

The robot incorporates tooling consisting of two large bore tubes (~1/2" dia.) to supply a large volume of cleaning air.

When our personnel visited the site, the system did not appear to have any type of air circulation system and was extremely noisy despite efforts to insulate the booth walls. This is because the ends of the booth are open to the main building.

All the robot's available controller memory is used on this application, although there are only two types of bogies.

Note that many of the identified shortcomings with the system described are being addressed in a second installation currently being implemented in another shop.

6/ How Robotics Can Improve Efficiency at the TTC Wilson Carhouse

Having accepted Vadeko's proposal to perform a feasibility study, MTO requested that the focus of the work be carried out at the Wilson carhouse. Undercar cleaning is performed at this location and it is considered most appropriate for installing a new automated system. Two cleaning operations are performed at the Wilson carhouse: blowdown and degreasing.

The purpose of blowdown is to remove dirt from the underside of the railcar where it builds up, inhibiting maintenance; it also creates a potential fire hazard in the area of the electrical components and the brake assemblies and increases wear on the components. In order to perform the blowdown operation, the operator wears protective clothing and a breathing apparatus. At Wilson, there is an environmental problem stemming from the fact that blowdown is performed in the main building (on track #14) as clouds of dust drift out into the rest of the carhouse where other workers perform their daily duties.

The present solution, although not ideal, is that the blowdown is performed first thing in the morning, allowing sufficient time for some of the dust to settle throughout the carhouse prior to commencement of the normal day shift.

Several drawbacks are immediately apparent:

- The process takes up valuable track space in the carhouse, which could be better utilized for other maintenance operations.
- The dust settles throughout the carhouse requiring regular clean-up.
- The dust that accumulates enters other vehicles, equipment, and components, transposing and aggravating the problem.
- Two operators are required to perform the task prior to the normal shift, making special arrangements for supervision necessary.

- The process leaves no room for flexibility in regard to the quantity of, and order in which, railcars are to be processed.

The major objectives of the study were not only to establish that robotics could be applied to railcar undercar cleaning, but also how such a system could be applied at the Wilson carhouse so that the logistics of operation would be improved.

Blowdown, as described earlier in this report, uses high volumes of pressurized shop air to loosen and remove dirt and dust mainly from electrical underbody and bogie components. This operation is performed approximately six times per year prior to regular maintenance checks.

Undercar degreasing is performed on an isolated track (#11) where water at a high pressure (1500 psig) is used to wash the underside of the car including bogie components and coupling areas where large quantities of grease accumulate.

Grease from automatic grease stations along the tracks spreads and builds up on critical components of the railcar. This grease is a potential fire hazard for any railcar not frequently and thoroughly cleaned. Consequently, all railcars are scheduled to undergo thorough degreasing twice yearly.

As with the blowdown operation, there are problems with the degreasing operation. The job is extremely unpleasant for the operator, who must wear heavy waterproof clothing and stand under the railcar as dirt and water constantly fall from the components as they are cleaned. There is no acceptable sequence that will allow the operator to stand away from under the dripping vehicle.

Although the cleaning booth and operator are well equipped for the cleaning itself, the operation remains highly undesirable. The result is that the level of cleaning varies greatly from operator to operator who attempt to complete the task as quickly as possible and consequently do not perform the job effectively. When the job is performed effectively, it can take up to five hours so that throughput is very low.

A major difference between blowdown and degreasing is that blowdown, in which existing covers are removed, cleans electrical parts; whereas additional protective covers are used over electrical parts during degreasing and care must be taken to prevent water ingress into those components.

The introduction of robotics as proved feasible by this study would permit the blowdown and degreasing operations to be performed both quickly and efficiently and in one central location. It would also minimize the problem of dust in the carhouse, greatly improving the cleaning efficiency and, therefore, reliability and railcar life.

In addition, the use of robotics would not only allow TTC personnel to be removed from an extremely unpleasant atmosphere, but it would also produce numerous tangible and intangible benefits that make the proposition highly desirable in terms of cost savings.

7/ On-Site Testing

7.1/ Purpose and Benefits of the Tests

As the study progressed through a variety of investigations into areas such as:

- selection of suitable robot types,
- identification of number of robots required,
- methods for moving the robots or the railcar,
- methods of correcting robot program position for various railcar positions, and
- implementation at the Wilson carhouse,

an actual on-site test program was initiated and performed at the Wilson carhouse using a DeVilbiss painting robot, which could be manually moved on a track alongside a railcar in the present degreasing bay.

Initially intended to prove its ability to reach various areas of the railcar, the robot played a far greater role.

Equipped with an array of tools to perform either blowdown or degreasing, the robot was used to perform many evaluations of the existing and new spray nozzle designs. This permitted the study team to produce a configuration that exactly matched the existing set-up.

Another bonus of having the robot on-site was the opportunity to introduce the system to the existing operators and other members of the maintenance staff. Although initially skeptical of the robot's capabilities, when the TTC staff were given a brief introduction to the robot's operating functions, each of them quickly mastered the programming method and produced short cleaning routines.

Having witnessed first-hand the ease with which the robot could be taught and after an explanation of how a fully operational system would function, the TTC staff appeared to be highly enthusiastic and keen to see such a system installed.

Another benefit of having the robot on-site was the many demonstrations performed for groups of TTC and MTO personnel, culminating in a full demonstration held on Friday February 12th, 1988. At this demonstration, many representatives of MTO and TTC senior staff were present, including personnel from bus and streetcar operations.

7.2/ On-Site Test Description

The demonstrations were performed using a robot lent to Vadeko by DeVilbiss head office in Toledo, Ohio at no cost to the project. This was a TR-450 industrial finishing robot, which was adapted to suit TTC requirements.

In order to adapt the robot for spraying air and water, it was equipped with a special tool at the end of the arm that could be easily changed to accept a variety of spray nozzle lengths and configurations including angles and tip sizes.

A valve pack was built to allow the robot to turn on air or water during its operation and a control panel was built to interface the robot controller with the valve pack. Finally, the valve pack was hooked into the existing air and water lines. This set-up produced a robot that could sit along side a railcar, however, like most robots, its reach was very limited in terms of the length of a railcar. Therefore, a ten-foot track was made that allowed the robot to be positioned next to the component to be cleaned without moving the railcar.

Prior to starting the testing of actual railcar cleaning, a series of tests were performed to evaluate the existing spray equipment since there were no available data in regard to its pressure, flow, and pattern characteristics.

The existing set-up requirements established, new spray nozzles were tested until a suitable match was found. The representative spray nozzles were then used for the automatic railcar cleaning tests.

thereby eliminating one form of inconsistency and giving the robot a fair chance of success.

The DeVilbiss robot is a "continuous path" style robot, powered by hydraulic actuators, which are monitored by resolver feedback devices for accurate positioning. This type of robot is typically used in painting applications primarily because it is explosion-proof and because continuous path means it can be led through a series of movements by an experienced painter and the robot controller will record exactly the path the robot moved through.

The robot is instructed to repeat the operation and is then capable of continuously performing the movements exactly as they were first "taught" to it.

This type of robot is ideal for this application for two reasons. First, because it is hydraulic, there are few electrical components on the robot manipulator arm, which is desired in such a wet environment. The second reason is its lead-through capabilities that make the teaching of the cleaning routines very simple to perform.

Once set up, the robot was taught a series of programs, each for the cleaning of a different section of the railcar. Special attention was paid to the cleaning of the bogies and brake areas, where large amounts of grease and dirt can cause problems.

The tests proved to be highly successful and the cleaning achieved was as good as could be expected from a conscientious human operator.

Three other problems needed to be addressed in the demonstration to obtain feasibility data for implementation: difficulties in reach, access, and in locating the longitudinal and vertical portions of the components to be cleaned.

The tests allowed the evaluation of the reach requirements of the robot and established that a third robot is necessary under the railcar in addition to robots on either side.

Height is a concern because wheel wear on the bogies lowers the components and when the wheels are reground it is common practice

to shim the bogies so that the body of the railcar is maintained at platform height. This puts the bogies below the normal height, however the components attached to the body could be almost anywhere in between. During the tests, a Honeywell Visitronic vision system was used to demonstrate the ability to locate the longitudinal and vertical positons of the railcar equipment. The vision system uses a TV camera to locate the hub of the wheel of the railcar; and then to calculate its position relative to the height of the railhead and to the distances for railcar equipment.

8/ Demonstrations of the TTC Robot

During the robot proof of principle testing, several demonstrations were held for various MTO and TTC personnel. These included actual hands-on programming of the robot by maintenance staff so that they could see for themselves how easily the robot can be taught the cleaning cycles for the system.

Once such a system is installed, it will be these teaching operations that the maintenance staff will have to perform for new railcar types as they are introduced to the TTC system and to periodically update cleaning produres to existing cars.

Once testing was completed, several formal demonstrations were performed and a final presentation was given on Friday February 12th, 1988 to senior MTO and TTC personnel and Mr. David Holappa, Project Manager for the Long Island Railroad robotic undercar cleaning system. Mr. Holappa gave a brief talk on the Long Island system and announced that Vadeko International Inc. of Toronto had recently been awarded the contract to design, build, and install the system despite very stiff competition from U.S. companies.

As part of the demonstration, Mr. Wojtek Wiercienski, Research Engineer at MTO and promoter of the use of robotics within the ministry's jurisdiction, gave a slide and verbal presentation of similar systems throughout the world and provided insight into other robotic applications that MTO is investigating.

Other projects identified as suitable for robotics were the cleaning of streetcars, which suffer from severe corrosion problems, the cleaning of bus engines and brake assemblies, bus refuelling, and internal railcar cleaning.

To augment the highly successful feasibility study, the Ministry of Transportation has produced a fifteen-minute promotional film, detailing the potential for robotics within North American transportation authorities, and highlighting the importance of the study of how robots can be used in undercar cleaning.

9/ Other Applications for Robotics within the TTC

As a result of preliminary studies by MTO, several other robotic applications have been discussed and should be seriously considered. Some of these are:

- Cleaning the underside of streetcars
- Cleaning bus engines
- Cleaning bus brake assemblies
- Refuelling buses

Through the installation of pilot projects such as the Wilson carhouse undercar cleaning system, the full capabilities of robots may be better appreciated. Once demonstrated, the use of robots will become more accepted and widespread.

During this project, some of the above initiatives were discussed among TTC, MTO, and Vadeko personnel. Some of these applications appear to offer significant benefits and, therefore, a more thorough investigation and feasibility study is recommended.

10/ Scope of Work Performed

The feasibility study was conducted in strict accordance with Vadeko's proposal of July 20, 1987. Section 11 of this report addresses the items in the proposal individually and outlines the factors to be considered in the design.

The proposal suggested that a variety of areas related to the introduction of industrial robots to subway car cleaning be investigated.

As part of the study, Vadeko offered to include actual on-site proof of principle testing with the use of an industrial robot installed adjacent to a subway car and capable of spraying TTC-supplied cleaning solution. These tests would provide firm evidence of the robot's ability to perform certain tasks.

The proposal listed the following topics to be studied and discussed as part of a report document to be presented to the Ministry of Transportation along with a verbal presentation.

Robot work envelope/dexterity

- Can a typical robot reach the various areas of the car?
- Proof of principle on-site test results

Quantity of robots required

- How many robots would be required to cover all areas of the rail car?

Robot selection

- Which robot manufacturer(s) supply products that would be suitable for the task?

Method of transfer

- What method of transportation is best suited (technically and financially) to achieve coverage of the length of the subway car?

  a) Transportation of the robots along car length (robot transfer tables) or;
  b) Transportation of subway car into robot work envelope (car progression system).

Combined air and water cleaning

- Can both types of cleaning be performed at one common location?
- What are the major advantages and disadvantages?

Daily throughput

- How many cars could be processed per day?
  a) Air cleaning only
  b) Water cleaning only
  c) Combined air and water

Air drying

- If water cleaning were performed, would a drying system be necessary? If so, what type?

Health and safety conditions

- Airborne contaminants
- Noise levels
- Safety barriers (operator protection)
- How would the contaminants (air- and waterborne) be collected and disposed of?
- Would the work area require protection to avoid undue contamination of the building?

Control system

- What method of supervisory/operator control and interface system would be required?
- What power and protection equipment (waterproofing etc.) is required?

Utilization of existing equipment

- Which of the existing buildings, if any, would be suitable?
- Can the existing air and water supply systems be used?
- Can the existing waste management system be used?

Manpower requirements

- How many operators would be required?
- What level of training would be required?
- What type of personnel would be required to maintain and service the automated system?

11/ Technical Discussion of the Robotic Application

This section begins with a brief technical description of the system, followed by a detailed discussion of each of the technical areas introduced in Section 10.

11.1/ System Overview

A robotic subway undercar cleaning system for the TTC would consist of three independently controlled industrial finishing robots. A master control system would allow the operator to remotely select and start the automatic operation of the robots. Each robot would be mounted on a 200-foot long linear track and include additional rotary and linear mechanisms to improve reach and operational capabilities. One robot would be located under the car between the tracks and the others would be on either side.

One robot would begin operation by inspecting the railcar's position within the booth and the master controller would use that information to accurately position the robots relative to the actual car position. An advantage of being able to position the spray tip close to the car components is that accuracy is maintained and maximum cleaning capacity is permitted. Each robot would be equipped with a variety of tool wands and be capable of exchanging wands automatically as commanded by the specific robot programs generated for cleaning each component on the railcar.

In order to cope with the variety of railcar styles, the operator will input the vehicle numbers so that the master controller can select the correct robot program.

The operator can indicate whether the car is to be blowndown or degreased. The operator will also have to remove certain covers on the car components to allow robot access during blowdown operations, plus cover some electrical components prior to degreasing. In some cases, the operator may be required to perform limited cleaning in difficult-to-reach areas. Special safety features will be built in to ensure that the human and the robot do not share the

same workspace at the same time. Although the operator will have to perform some cleaning of the equipment on a periodic basis, the robots can be instructed to clean the tracks, booth walls, and themselves (using compressed air only) at the end of a shift as required by the operator.

In order to improve safety in the unattended cleaning area, closed circuit television cameras will relay scenes of the area to the operator, who will be in a control room on the platform above.

11.2/ Robot Work Envelope/Dexterity

Due to the height of the railcar above the booth floor and the booth size (i.e. track to walls, floor to platform height), no single existing commercially available robot is able to reach both the centre and outsides of the railcar, and still fit under the railcar while on a track.

Following a series of trial design layouts, it was established that a system with three selected commercially available robots could reach all areas of the railcar if they incorporate a tool change system (established technology) with a variety of wand lengths and spray tip configurations.

On-site testing has indicated that each robot would require a maximum of five tools.

As most off-the-shelf robotic tool change systems are designed for 100 psig pressure (suitable for delivery of blowdown air, but insufficient for degreasing), it is necessary to modify or develop a system capable of sealing 1500 psig pressure (for delivery of water for degreasing).

Although the presence of electrical controls should be avoided (especially at the end of the robot arm) some form of wand detection should be included to ensure that the tool is attached and detached prior to each operation. Each tool must be firmly held during rapid travel along the track. Also, a "breakaway" adaptor must be included between the robot tool flange and the tool in order to detect excessive load on the tool if the robot inadvertently touches the railcar.

Dexterity of the robot arms and orientation of axes (end of arm motion) is very important in this operation. On-site investigation has shown that, in order to meet this requirement, a minimum of five basic axes must be present on the robot.

On-site testing has shown that a sixth axis is advantageous in directing a "flat fan" spray at the railcar. However, a six-axis system requires end of arm drive mechanisms, which are typically bulky and inhibit access to several areas of the railcar, especially around the bogies. Care must be taken to ensure that the end-of-arm mechanism does not completely inhibit cleaning capacity.

Even though a "cone" spray does not need to be oriented and requires nothing more than direction, it is recommended that cleaning performance not be sacrificed by incorporating a cone spray, as a cone spray has less cleaning ability than a flat fan (due to reduced force from a higher coverage per unit of pressure).

Because efficiency of cleaning is considered of prime importance, the six-axis system with the flat fan tip is preferrable.

11.3/ Quantity of Robots Required

The robots under consideration are typically articulated types with their two major arms mounted in a vertical plane. This basic feature prevents the robot from reaching around corners or, more specifically, around the wheels into the bogie area. Because of this, it is not feasible for robots mounted on the outside of the railcar to reach in to fully clean the areas of the bogie both underneath and between the bogie and the vehicle bodywork (floor). Consequently, it is necessary to include a third robot between the tracks underneath the railcar.

The third robot must be short enough to sit below the railcar and to pass under the bogie as it traverses along its track under the railcar. However, it must also be able to reach up and over the top of the bogie when in position.

These requirements will greatly limit the selection of commercially available robots that may be used for this application. However, the

demonstration indicated that there is at least one commercially available system that can do the job.

11.4/ Robot Selection

The selection of a particular robot manufacturer and model should be based on technical and other criteria, including:

- Work envelope
- Articulation (dexterity)
- Reach and access capabilities of end of arm
- Overall height
- Protection from contaminants (water/dust)
- Ease of programming and operation
- Payload capacity
- Repeatability
- Controllability (from external sources)
- Reliability
- Ease of maintenance
- Technical support (spares and maintenance)
- Cost

Although there is a wide range of industrial robots capable of fulfilling some of the requirements of this system, few will meet all of the major technical requirements that are essential for the success of the project.

The robot selected must satisfy the following basic requirements. It must:

- be able to reach all areas of the railcar and booth walls with tool changes;
- fit under the railcar yet reach all the areas required (this requirement is for the central robot only);
- not require major modifications to the standard components;
- be a common unit throughout all three units;

- be able to resist the effects of water, dust, and cleaning materials (Finishing robots are recommended and hydraulic ones are preferred. If electrically driven robots are used, they must be fully sealed);
- be able to support and manipulate various tools weighing up to 5 kg (11 lb);
- include point-to-point and continuous-path, lead-through teaching and playback capabilities;
- include high volume, non-volatile program storage, automatically accessible by the robot controller, and permit rapid program downloading to the robot from the system controller;
- include some form of multiple positional offset (x and z axes) capability to suit various wheel diameter and railcar positions;
- have a positional repeatability of +/- 2 mm (0.080 in) or better;
- have a manipulator incorporating easily maintainable mechanisms;
- be supplied by a manufacturer well represented in the province of Ontario with a proven track record and with the stability to provide ongoing support throughout the life of the equipment.

11.5/ Method of Transfer

To enable the robots to clean the full length of the railcar, two basic methods of transportation were considered: moving the railcar and moving the robots.

Moving the Railcar

Initially, moving the railcar appeared to be the most viable alternative because it is incorporated in the present blowdown procedure; one operator drives the vehicle in stages while another operator cleans the car and instructs the driver when to start and stop.

However, when one considers automating this process with a car progression system, a few major technical and logistical disadvantages become apparent:

- An area at least twice the length of a pair of railcars would be required, which would not be available at the Wilson yard without major building re-organization to create a drying area.
- A car progression system would not in itself be able to position the railcar accurately enough for the robots to perform their task.
- A car progression system would inhibit access of the robots to the railcar.
- The time taken to move the railcar would be excessive compared to the alternative of moving the robot.
- The cleaning procedure would be forced to follow the advancement of the railcar and consequently the robots would not be able to:
  - move back and forth along the railcar to obtain improved access to some components;
  - perform as much work with one wand spray tip as possible prior to change over or;
  - clean the booth walls etc. upon completion.

Moving the Robots

A system that moves the robots along a stationary railcar would not be subject to the disadvantages mentioned above; however, the use of linear tracks carrying a robot would incur other disadvantages, because the tracks would:

- Take up a large area of floor space;
- Have an initial investment cost that is two to three times the cost of a progression system;
- Still require some form of inspection and correction for railcar positioning in the booth;
- Require more cleaning and maintenance.

Selection

The disadvantages of the car progression system far outweigh those of the robot track system for both technical and logistical reasons. Consequently, the use of three linear tracks is recommended for this particular application.

Credence is given to this conclusion by the fact that the Long Island Railroad Company, which has only three-foot high rails, has commissioned a two-robot system for blowdown, which is to incorporate linear tracks that will be effective in a tight operating space. Also, they have a progression system that is only used to bring the railcars into the building.

Track Design

There are several major design criteria that any track must adhere to if it is to operate satisfactorily and have an acceptable life-span.

- A rigid platform must be created. The robot must not be able to leave the track.
- Positioning repeatability must be held to +/- 6 mm (0.25 in) along its length and +/- 3 mm (0.12 in) across its width and in its height.
- Any exposed steel components must be corrosion resistant, i.e., stainless steel.
- Any bearings, guides, etc., must clean the track as it traverses.
- Must incorporate some form of protected/sealed flexible conduit/track for the lay of cables and hoses.
- Must include overtravel switches connected to the hardwired emergency stop circuitry.
- Must include collision switches in case of obstructions within the track.

11.6/ Combined Air and Water Cleaning

Technically, there are no reasons why the system could not perform either blowdown (air) or degreasing (water) as required by the operator. When the car comes into the cleaning area, a display on a computer screen in the control booth prompts the operator to input the vehicle number of the car, type of cleaning required, the degree of

"dirtiness," etc. With this information, the control system instructs the robot to automatically carry out the required sequences to clean the car.

Due to the greatly differing flow requirements, the tip sizes are different for air (higher flow rates required) and water. The spray tips will be quick connect/disconnect types to improve efficiency.

Logistically, with the throughput requirements detailed in the next section, both types of cleaning are feasible if three shifts are utilized and degreasing is performed on the night shift in order to allow use of the wheel grinding area for drying of the first of three pairs of railcars processed.

11.7/ Daily Throughput

There are two criteria to be met regarding throughput capacity of the system:

- Desired throughput per day
  - blowdown
  - degreasing

- Required frequency of cleaning individual railcars per year
  - blowdown
  - degreasing

It is the latter requirement based on the fleet size that sets the throughput requirement of the system.

In order to evaluate the capacity of the system, it must first be established how long it will take the system to clean a car for blowdown and degreasing.

Blowdown Capacity
The present manual system takes approximately four hours to complete three pairs of cars, that is, six pairs in one eight-hour shift. This includes the time needed to shuffle cars and to progress them over the pit as well as to do the actual blowdown. It is estimated that the actual blowdown and progression time is in the order of one hour per pair of cars. Because a robotic system does not need progression time and because three robots will be perfoming the work of one person, it is safe to assume that the blowdown of one pair of cars will take less than 30 minutes.

Degreasing Capacity
At the present time, degreasing one pair of cars takes one eight-hour shift. The actual cleaning time is between one and four hours, with the remaining time left for drying.

To be conservative, we will assume that each pair requires the maximum cleaning time. However, because three robots are now doing the work of one man, it is conservatively estimated that each car pair will be cleaned in 60 minutes. This is consistent with the results achieved during the demonstrations. However, in order to keep the line moving, the cars need to be dried at a similar rate.

By allowing an additional 30 minutes to set up each car pair and a further 30 minutes to move degreased cars to the drying area, the overall times for each type become

Blowdown = 60 minutes per car pair or 8 pairs per shift
Degreasing = 120 minutes per car pair or 4 pairs per shift

These figures are considered conservative. Therefore, the throughput capabilities detailed below will be achievable.

Requirements
The current throughput of the existing system on a daily basis is:

Blowdown = 6 pairs (in two locations)
Degreasing = 3 pairs (at Wilson only)

When 250 working days per year are used, the cleaning frequencies of the 310-pair fleet for each operation is calculated to be:

Blowdown =	approximately 5 times per year for each car (6 is the current targetted number)
Degreasing =	more than 2 times per year for each car (2 is the targetted number)

With the increased capacities of a robotic system (8 car pairs versus the current 6 for blowdown and 4 pairs for the robotic degreasing versus 3 for the manual system), the existing targetted requirements are easily achieved within one blowdown and one degreasing shift – both in one location. This further allows for increased capacity and/or increased cleaning frequencies if a third shift is added.

Capabilities of the System

Having established the capacity of the system and the actual operational requirements, we can now consider the logistics of operating at the Wilson carhouse with regard to throughput of the system on a daily basis.

• Blowdown

It is clear that in order to meet the frequency requirements of the fleet, the blowdown operation can be performed on a single-shift basis.

• Degreasing

Although the capacity of the system exceeds the requirements, the Wilson carhouse performs wheel grinding in the north section of track #11 whereas the cleaning will take place in the south end of this track.

Consequently, it is important to ensure that lead cars on the automated line are dried in time to accommodate those coming off the wash station.

11.8/ Air Drying

The present throughput requirements of the manual system do not require the use of an active drying system. It is desirable to accelerate the drying time when an automated system is used. This could be achieved by having the robot blow air to remove the layer particles of water from the car. In addition, an air recirculation system that heats and de-humidifies the air (in the room where the car is dried) may be used. Alternatively, if scheduling permits, the existing wheel grinding area could be used to continue to "drip dry" the cars.

11.9/ Health and Safety Conditions

There are several areas of health and safety that need to be addressed in any cleaning system. The major areas are discussed here.

Airborne Contaminants

Probably the major reason for implementing an automated cleaning system is to remove the operator from the dirty and unpleasant blowdown and degreasing atmosphere. The addition of a second platform to produce a lower room will control the dust and, by removing the operator from the room entirely, solve the problems associated with airborne contaminants (dust) .

Presently, blowdown is performed very early in the morning in order to allow the airborne contaminants to settle. Any attempt to blow down during a normal shift creates an unacceptable atmosphere in the carhouse for other workers who are not wearing protective equipment. Consequently, it is not practical to expand the capacity of the current system using manual methods.

In the robotic system, the operator will be located in a small control room on the platform above the cleaning area. This room will be air conditioned and the operator will be able to monitor the progress of the system via remote cameras.

Noise Levels

Noise generated by the cleaning process will be limited to the isolated and empty cleaning area and should not be excessive.

Safety Barriers

To ensure that unauthorized entry into the cleaning area does not occur, the addition of walls and doors at either end of the booth will be required. All doors with access to the booth will include interlocking sensors to allow the system to halt operation if a door is opened during cleaning. In addition, the operator will have a key to prevent accidental restarting by someone else when he or she is in the pit with the door closed.

Waste Management

The present drain-off facilities on track #11 are sufficient to continue removal of the undercar cleaning debris, however the addition of blowdown in that location will require additional resources.

The addition of a self-supporting second platform on the west side of the track is required to produce a separate cleaning area in the lower portion of the building. The platform will prevent airborne contaminants from entering the upper area (except at the ends of the railcar) and will improve the efficiency of the proposed air circulation system. The introduction of a negative room pressure will prevent contaminants from entering the upper area.

Several methods of airborne contaminant removal were investigated:

- Local exhaust at the end of the robot arm;
- Semi-local exhaust at the base of the robot (similar to the existing cyclone system);
- Room exhaust;
- Room recirculation.

These are described below:

- A Localized and Semi-Localized Exhaust

A "Celsius" system made by Tykron Industries could supply either local or semi-local exhaust up to 2 500 cubic feet per minute (cfm) using an eight-inch diameter hood at a maximum distance of 36 inches from the source. This system incorporates a common rail which allows the exhaust pipe to travel along its length as it moves with the robot.

Including a cyclone filtering system, a single line would cost approximately $20,000 and only remove 10 to 20% of the airborne contaminants at best.

- Room Exhaust

Assuming the cleaning area has an approximate volume of 50 000 cubic feet (200 x 25 x 10 ft), a system to remove the air, filter it, and reheat the replacement air would cost approximately $50,000 and an average of $50,000 per year to operate. This works out to $1 per cubic foot.

- Room Recirculation

A system designed to recirculate the air would cost up to $100,000. However the operating costs would be only $20,000 per year.

This method will remove up to 70% of the contaminants, with the remainder falling to the floor area where it will be washed away during degreasing.

In summary, any type of local or semi-local exhaust of the air would be very inefficient; between 10 to 20% removal of the contamination.

The most efficient method would be to exhaust or recirculate the room atmosphere. The addition of a second platform, walls, and doors will keep the room volume to a minimum.

Total exhaust of the room's air to atmosphere would be both very costly in heating, and environmentally unacceptable unless forced through filters (cyclone etc.) on the way out of the building.

The best method would be the use of ducts on either side of the room to pass recirculating air across the room and then filter, dehumidify, and return the air to the room. Although initially the most expensive of the methods discussed, the long-term operating costs make this method viable.

Grease Build-Up
One of the purposes of degreasing is to remove excess grease in certain areas, such as the brakes and couplers. This build-up is caused by wheel activated wayside greasing machines, and must be removed in order to reduce the risk of fire.

During cleaning, the grease falls down and builds up under the tracks and in the traps, then has to be removed by the building maintenance staff.

In the new system, this procedure would have to be maintained, but it would be the operator's responsibility to initiate the clean up. Obviously, the frequency of clean-up will become greater as the throughput of the facility increases.

11.11/ Control System

Controller Type
To control three robots complete with tracks, a centralized master control system is required. This system should be capable of performing multi-axis control, communications, and digital input/output signalling. Also, the controller should be programmable in a high-level programming language for ease of operation.

The controller would include a colour monitor display (CRT), keyboard, printer, and hard and floppy disk drives for program storage. With software developed for this application the system should be easy to set up and operate. The operator should be prompted through a series of menu-driven screens to select the type of operation to be performed and the system should output via the screen and printer supplying the status of the system at all times. The system should be designed in a manner that would make it easy for the operator, not only to perform routine operations (blowdown and degreasing), but also to make program changes for new car types, etc.

Included in the system's operating requirements would be the following:

- The ability to communicate with three robot controllers in order to instruct which programs to load and execute. It may be necessary to perform up/down loading of programs to and from a mass storage device dynamically.

- The ability to communicate with the car inspection system to obtain positional status of the railcar location.

- The ability to control auxiliary axes if required for the system.

Control Panel

An operator's control panel would be designed for this application and all equipment would be built into it. The operator would sit at the panel and would have one monitor for the control system operation and at least one other monitor for the closed circuit television (CCTV) cameras located in the booth. The operator should be able to switch between cameras at will.

A keyboard should be the main form of operation for the system, however the operator should not require any special training as the system should prompt the operator with menu selections which require the pressing of number keys and the enter key. Invalid selections should give a short message and prompt the operator to try again.

The panel should be user-friendly and include a printer for hard copy data such as the number of cars processed and other management information. A floppy disk drive should be used to provide off-line storage of the programs and should require a short sequence to "boot" the system after a full shut-down.

All robot controllers and related equipment should also be located in the control room which will have to be long and narrow in order to fit onto the platform.

The control room should be situated centrally to the carpair being cleaned to keep control cable lengths to a minimum. Extensive cable lengths can cause communication errors especially if near other voltage lines.

Power Requirements
In order to supply the control room with adequate power, the facility's supply system should be configured to give a balanced single and three-phase supply approximately as follows:

3 lines @ 550 V ac - 3 Phase - 15 amps each
6 lines @ 110 V ac - 1 Phase - 15 amps each

All electrical power and communication lines must be protected in suitable conduit and terminate in waterproof NEMA 4 enclosures.

All electrical signals interfacing with control equipment must be suitably fused and/or pass through opto-isolators for protection of low voltage circuitry.

Air Requirements
Suitable air lines are already located in the undercar cleaning area and are probably capable of providing the additional requirements of the two extra spray guns.

Wash Requirements
During on-site testing, at least two of the three wash systems were faulty. Therefore, it is recommended that either one common high-volume or three replacement wash systems be provided with the new system. In addition, the new system(s) should be capable of providing up to 2000 psi pressure (to be used on unpainted car surfaces) in order to take advantage of the robot's ability to handle higher pressures.

As in the current wash system, the new equipment must be capable of heating the water and adding detergent, as appropriate.

11.12/ Utilization of Existing Equipment

A major consideration for implementation of a robotic system would be the use of the existing equipment and facilities.

Existing Building
As required by the TTC, the existing undercar cleaning area on track #11 (south side) is suitable for both blowdown and degreasing operations.

Although the existing space is suitable to meet the present requirements, some modifications are needed:

- A second platform on the west side of track #11 is required. It must be self-supporting and not cause an obstruction to the robotic system. The purpose of the platform is to enclose the cleaning area and permit the recirculation of the air. It may cover the cleaning area only or the full length of the bay. This change will create an area upstairs suitable for internal vehicle cleaning, for example, ceiling fan cleaning.

- Walls are required to complete the separation of the cleaning area on the north side. These walls should include access doors and close off the area between the outer walls, the tracks, and the platforms; they should also produce a cleaning area suitable to store a pair of cars.

- Some of the grating supports between the tracks would have to be removed to accommodate track carrying the centre robot.

- The grating around the robot tracks would have to be modified.

- Air recirculation equipment for the booth area is required, as described in Section 12.

- A remote control room on the upper platform would have to be added.

Existing Air and Water Supply Systems

• The presence of air lines in the cleaning area will be sufficient for the new system.

• The existing wash systems should be replaced with three small or one large common system capable of supplying a minimum of 5 gallons per minute per robot at 2000 psig.

These systems should be located on the upper platform and incorporate large bore hoses to reduce pressure drop in the lines.

Existing Waste Management

As detailed previously, the existing waste management is sufficient for solid and larger particles caused by degreasing, but an air re-circulation system is required to filter contaminants from the air caused by blowdown.

11.13/ Manpower Requirements for Operations, Maintenance, and Service

Operators

The system supplied should be designed to be operated by one supervisory operator whose training will be minimized to the level of basic operations. The system should be menu-driven and include a simple, on-line help program to guide new operators through the sequence of operations for set-up, selection, and cleaning.

Other support staff may be required by the TTC to move the railcar into position. However, the operator should be capable of performing the following operations:

• Prepare the railcar for cleaning
  - remove covers for blowdown
  - cover electrical components for degreasing;
• Prepare the robot tools, by exchanging all five tool tips for either blowdown or degreasing;

- Confirm that the railcar is correctly positioned;
- Confirm that the robot equipment is correctly positioned for remote start-up;
- Ensure the cleaning area is clear of obstacles and personnel;
- Start the control system;
- Follow the menu-driven sequences at the control panel for operation
    - Select vehicle number or type
    - Select the type of cleaning
    - Select cleaning of booth, if required
    - Start operation
    - Stop operation in mid-cycle, if required;
- Monitor the system's progress via the CCTV and system monitors
- Be present throughout the process;
- Perform periodic cleaning of the cleaning system not reached by the robot, including the robots themselves;
- Perform some cleaning operations that the robots cannot perform due to reach or positioning limitations, if necessary.

Maintenance Staff

Several members of the maintenance staff should be instructed in the system's operations, maintenance, and repair procedures. This training should take place at the system integration facility, on-site, and at the major hardware supplier's facilities.

Alternatively, the TTC may prefer to contract out maintenance functions.

Cleaning Staff

Any existing staff currently responsible for removing grease build-up, etc., from the cleaning area should continue to do so.

Training

The system operators should undergo basic training, which should last a minimum of 40 hours, to enable them to carry out the normal operations of the system.

However, the maintenance staff should undergo indepth training to give them an understanding of all the major components, especially the robots and their controllers.

Some members of the staff (to be decided by TTC) should undergo training in the production and editing of new programs for both the master and the robot controllers. This will allow the TTC to independently produce new programs or change existing programs as the need arises.

12/ Logistics for Implementation at the Wilson Carhouse

Before an automated cleaning system at the Wilson carhouse can be implemented, there are several areas besides the robotic equipment that must be addressed.

12.1/ Changes to the Building (Structure)

Platform

In order to contain the airborne contaminants during blowdown, a second platform is required.

The platform should be self-supporting and there must not be any vertical beams or structures below the platform. The length of the platform should be a minimum of 200 feet (the length of a car pair) and may cover the full length of the present cleaning area (approximately 400 feet).

Walls/Doors

To help support the platform and to seal off the cleaning area, two short walls are required at the 200-foot position between the existing walls and the tracks. Each door will include a spring-loaded (auto close) door.

Any openings (doorways) into the area will also require spring-loaded doors.

Platform Curtains

Both platforms will require brush curtains to be mounted on the inner edge in order to seal the space between the platform and the railcar.

The curtains are to prevent airborne contaminants and water from spraying up between the platform and railcar.

Grate Supports (removal)
The concrete supports located between the tracks, used to support the steel grating, must be removed along the 200-foot cleaning area to accommodate the robot's track.

Grate Modifications
Upon installation of the robot system, the existing grating will require replacement or modification along most of the cleaning area.

Control Room
In order to house the control equipment and control panel, a long narrow control room must be constructed on the existing platform, mid-way along the cleaning area (to minimize cable lengths).
It should include one lockable door and large windows to give good visibility to the operator.

The room should be climate controlled (local air conditioner) in order to protect the operator and equipment from excessive temperatures and humidity.

Cleaning Area Air Exchange
In order to control the airborne contaminants during blowdown and high humidity during degreasing, a full air exchange system should be built into the cleaning area.

Large vents along the length of the room should be kept as close to the wall as possible to maintain clear access for the robot system, and may pass through the walls if desirable.

The air in the room should be recycled six times per hour and be filtered and dehumidified. Some heating may also be required.

Care should be taken to ensure that the humidity from the degreasing does not produce a severe corrosive effect.

12.2/ Support Equipment

Some additional equipment will be required to support the new installation.

Wash System
The existing wash systems are several years old and require constant maintenance. Therefore, either three separate or one common wash system should be installed on the upper platform.

Each robot requires a minimum of 5 gallons per minute at 1500 psig and preferably should be supplied with up to 2000 psig.

Track Mobile
In order to move the cars around the building without the use of power after a wash, a Track Mobile must be provided. A rebuilt unit would be sufficient and would cost less than $50,000.

The addition of a second platform will require redesign of the "bug" system in the cleaning area.

13.0/ Conclusions and Recommendations

This study has shown that it is technically, logistically, and economically feasible to implement and operate an automated system incorporating industrial robots for cleaning TTC subway cars at the TTC Wilson carhouse in Toronto.

It is recommended that the TTC seriously consider implementation of the system at Wilson.

13.1/ Conclusions

Number of Robots
Design studies and on-site testing indicate that three robots mounted on linear tracks could move along and clean all critical areas of the underside of the railcars.

Integration of Air and Water Cleaning
It is possible both technically (from an engineering standpoint) and logistically to combine both "blowdown" (air) and "degreasing" (water) in the existing degreasing location (track #11) of the Wilson carhouse. Interior "cyclone" cleaning may also be done at the same location.

Operating Shifts
The throughput of such a system would comfortably meet the requirements of the TTC by operating two shifts a day. The TTC recently implemented a three-shift degreasing operation at Wilson, but automated operation would require only two shifts for both degreasing and blowdown. Using robotics and keeping the three-shift operation, the TTC could do cleaning more frequently than is currently done and/or bring in additional cars from other yards.

Manpower Requirements
The use of one operator per shift is sufficient to operate the system.

Training Requirements
Although some staff training will be required in order to operate the system, existing employees can be easily trained.

More training will be required by the maintenance staff, who would take established courses conducted by the major hardware vendors. The TTC may wish these employees to receive additional training by the system supplier in order to modify cleaning programs and paths to suit newer car models as they are introduced to the fleet, or to modify cleaning procedures for existing ones.

Maintenance and Repair
The TTC could either sub-contract to the supplier or robot manufacturer, or a TTC employee could receive training to perform necessary repairs and maintenance. This is not such new technology that this would be infeasible; the necessary skill level already exists within the TTC.

System-Operator Interface
When operational, in order to clean a given vehicle, the operator will use a computer terminal to select the car type and the cleaning method (blowdown or degreasing) and to start and stop the system. All procedures for operating the system through the terminal will be user-friendly, employing a multiple-choice menu structure in a self-explanatory format. No programming knowledge will be required to clean a car.

Supply of On-line Data
Information from the cleaning robot control system and closed circuit television cameras will supply enough continuous on-line data on the status of the robotic system to allow the control booth to be located on the upper platform, remote from the actual operation.

Implementation at the Wilson Carhouse
The existing undercar cleaning area on track #11 will require the addition of a second platform plus separation walls and access doors.

The control room will be located on the existing platform. A large-scale air recirculation system will be required to remove contaminants and humidity from the cleaning area atmosphere.

New wash systems will be required to replace the existing undercar cleaning units. In the event of robot system malfunction, cleaning will continue at a lower level of performance. Of course, the TTC may revert to manual cleaning on a temporary basis, if needed.

13.2/ Recommendations

This report makes the following recommendations:

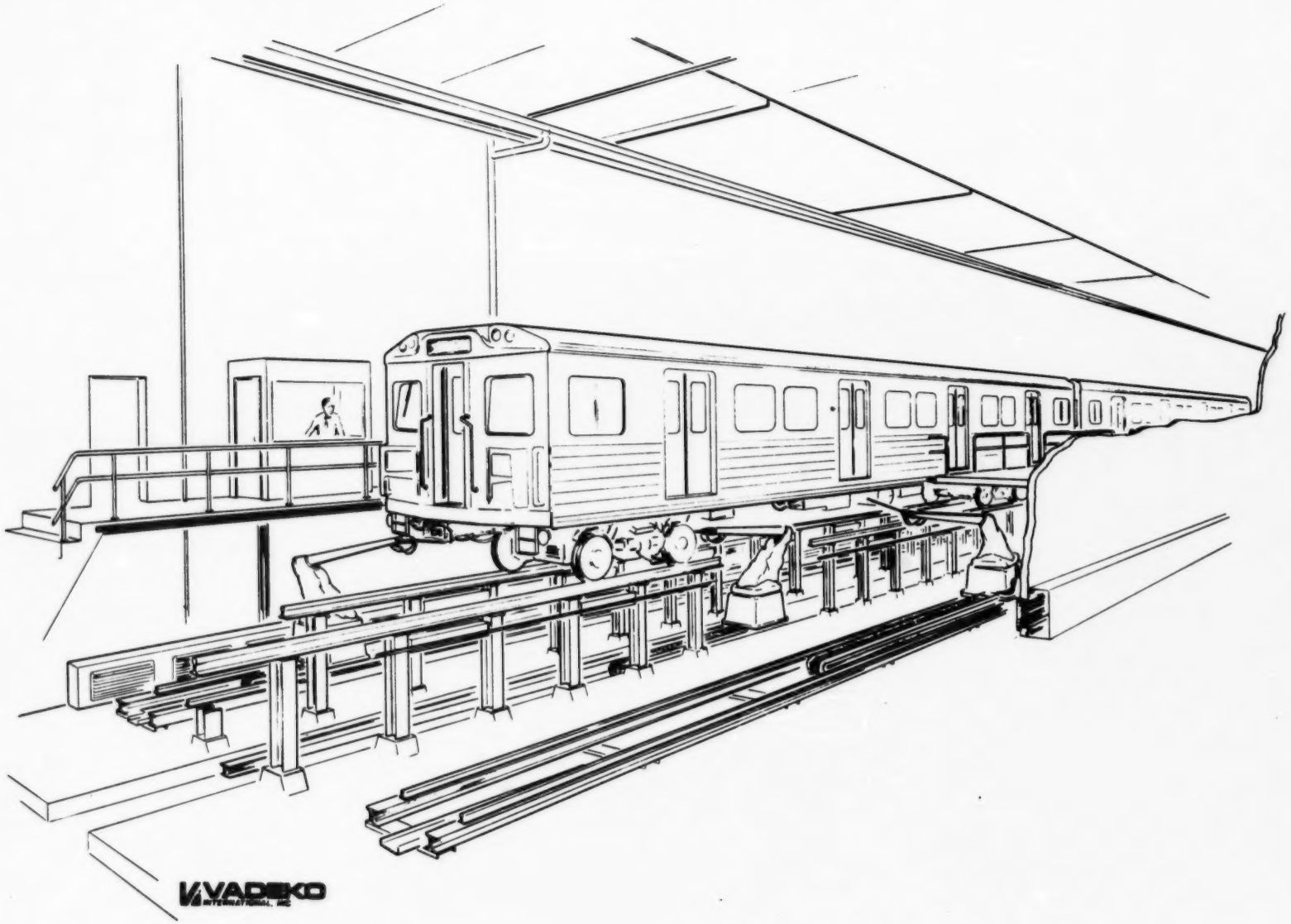
- That the TTC tender a contract to a capable engineering company for the full design, construction, installation, and commissioning of a robotic undercar cleaning system as specified in this report. Separate contracts should be tendered for the specified modifications to the Wilson carhouse facility.

- That the TTC continue to work with MTO as technical consultants and that the TTC seek appropriate funding for the project.

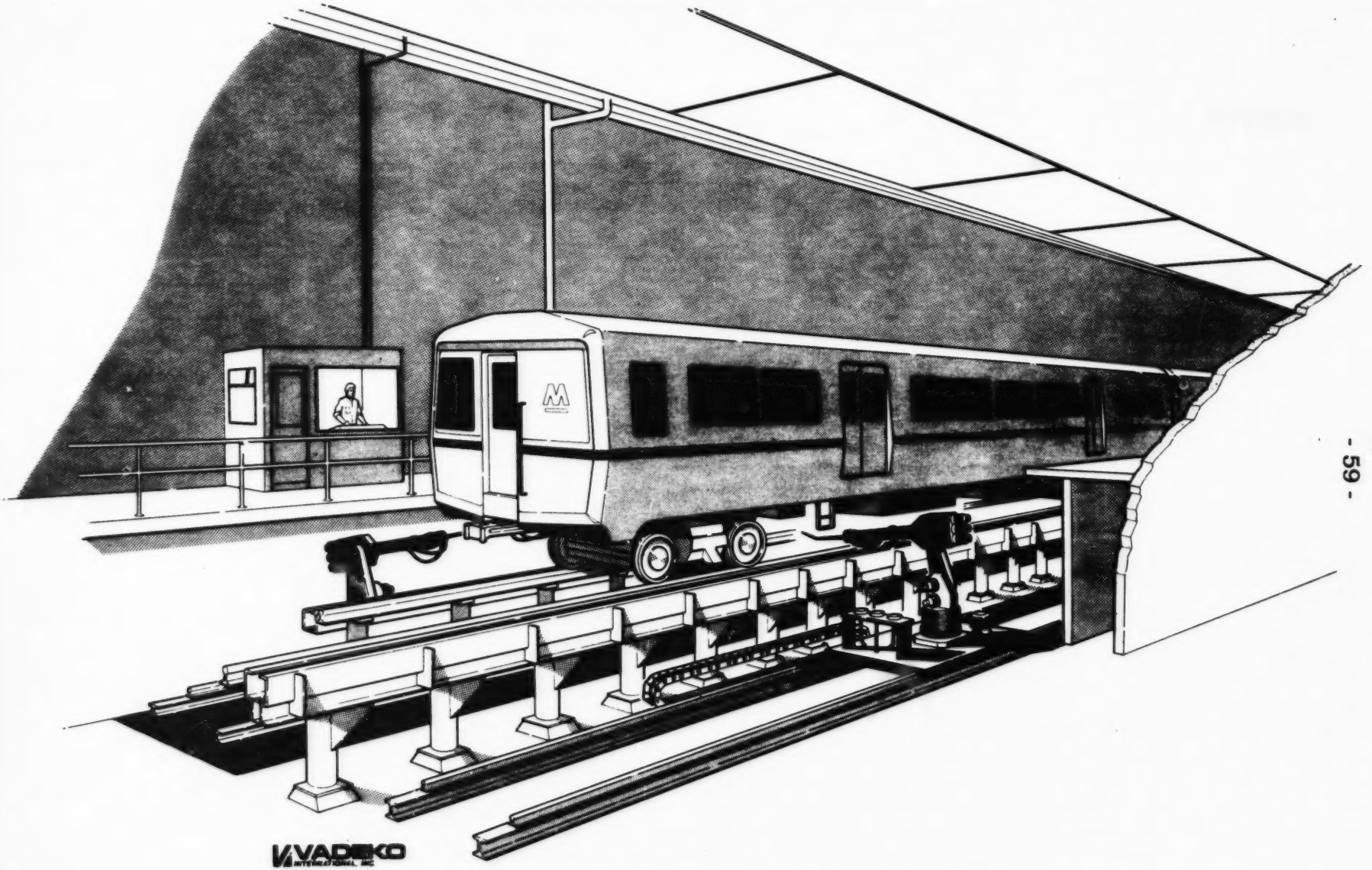
- That the project be handled and funded as a pilot project with the aim of demonstrating the potential for the introduction of similar systems at other TTC sites, particularly on streetcars, where significant cost savings could be realized as a result of the improved cleaning. In addition, this pilot project will provide baseline operational data on robotic systems. It will also provide assistance in evaluating the additional potential for robotics technologies, both at the TTC and in other Ontario transit properties.

- That an additional feasibility study be conducted to assess the potential for robotic systems; robotic applications in the Greenwood carhouse expansion, streetcar cleaning, bus brake cleaning, bus engine shampooing, and bus fuelling.

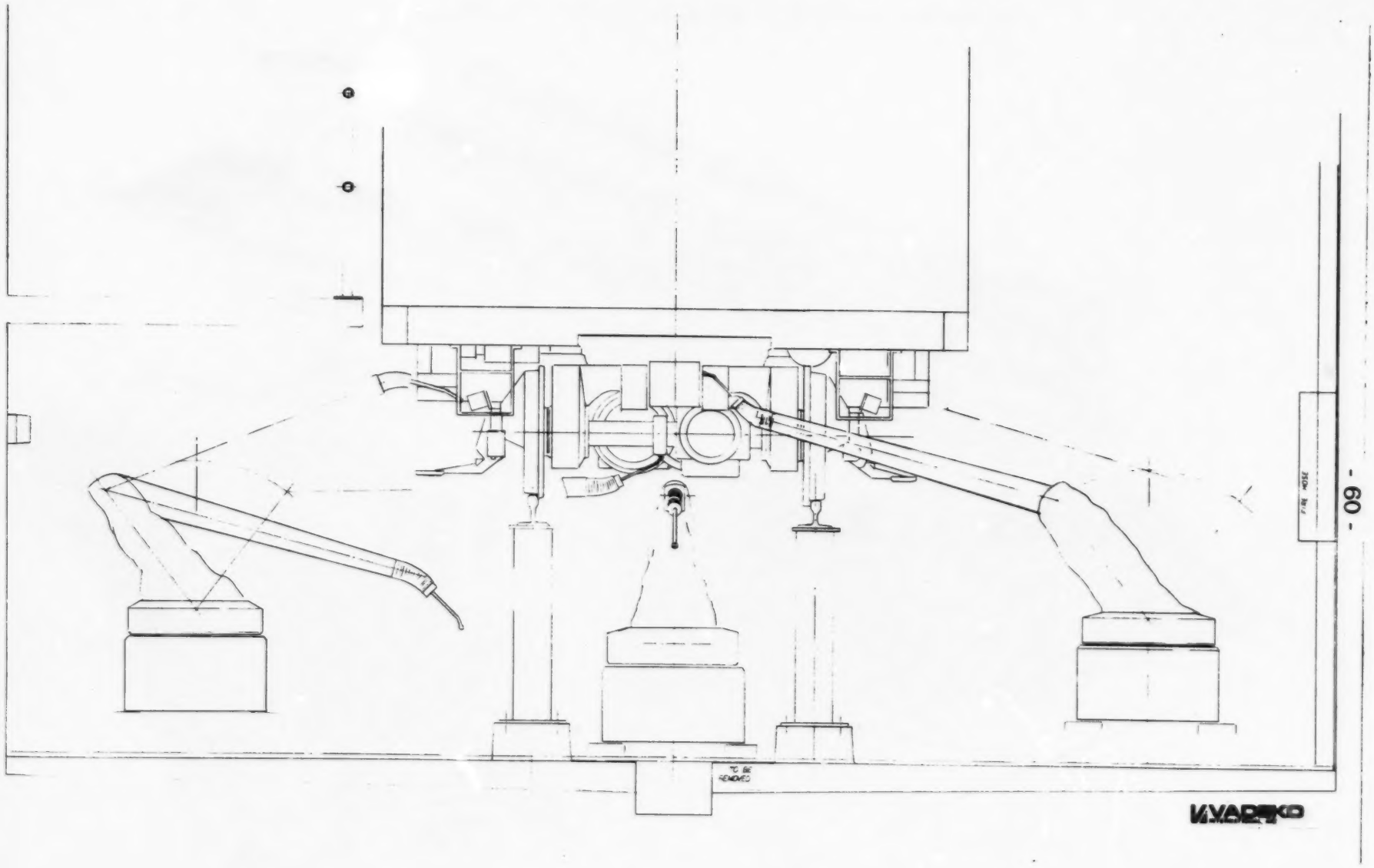
APPENDICES



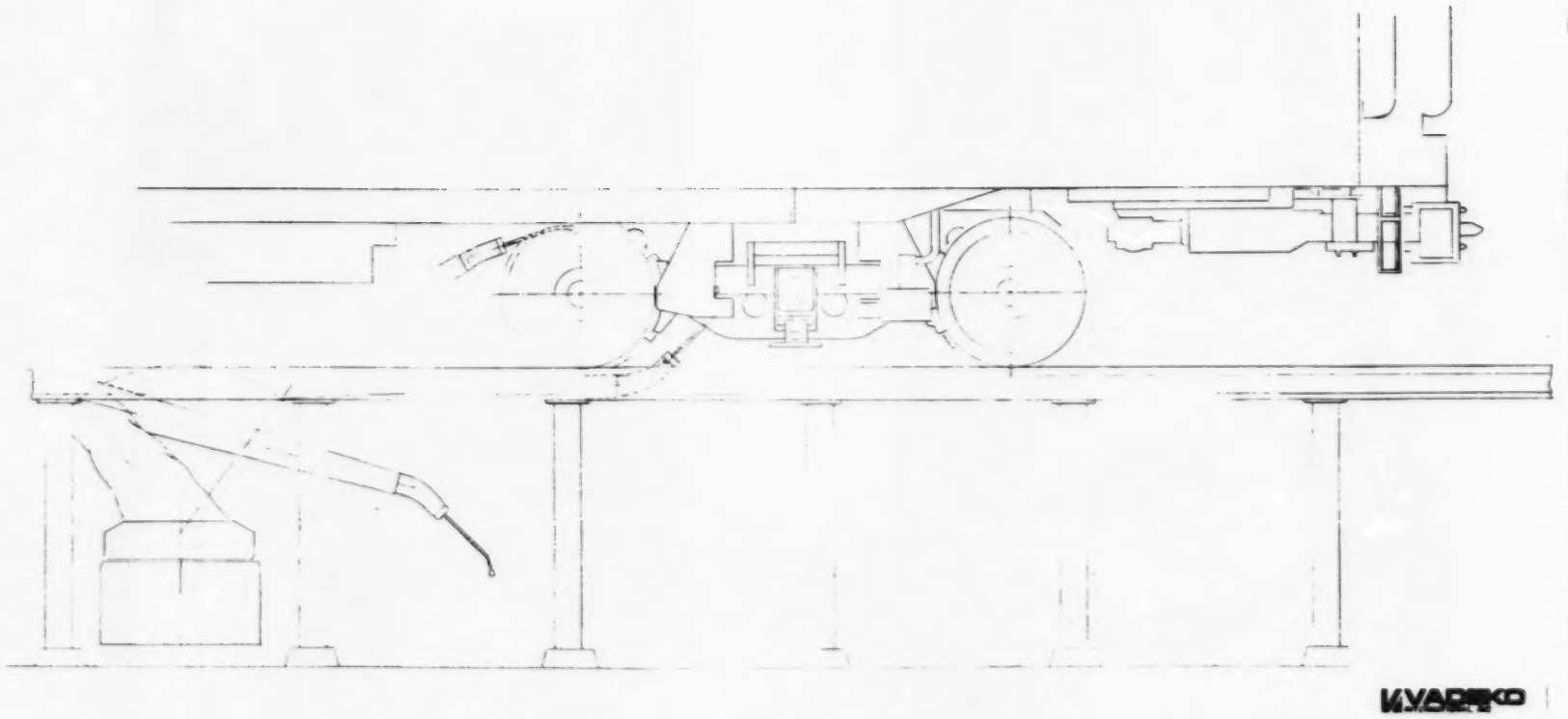
A/ Artist's Impression of Robotics at the TTC



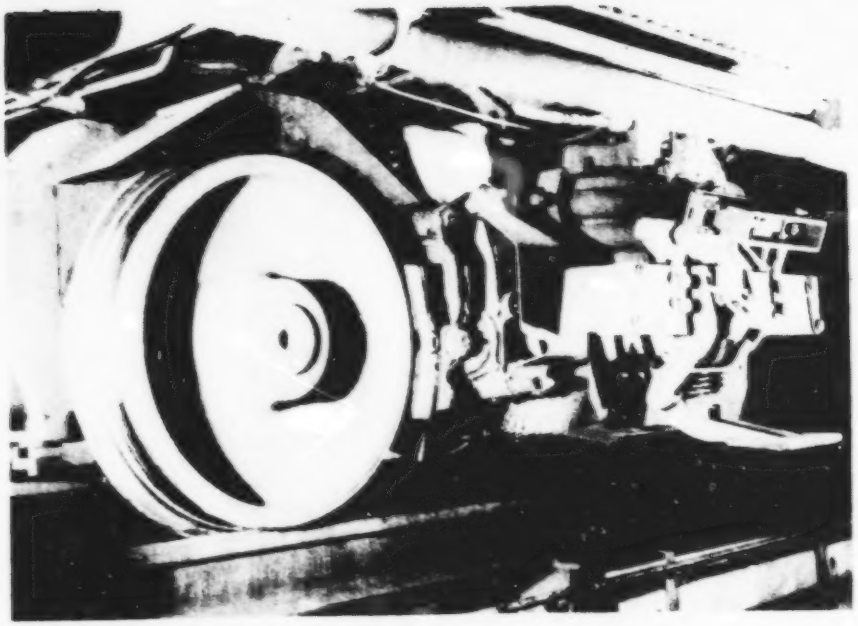
B/ Artist's Impression of the Long Island Installation



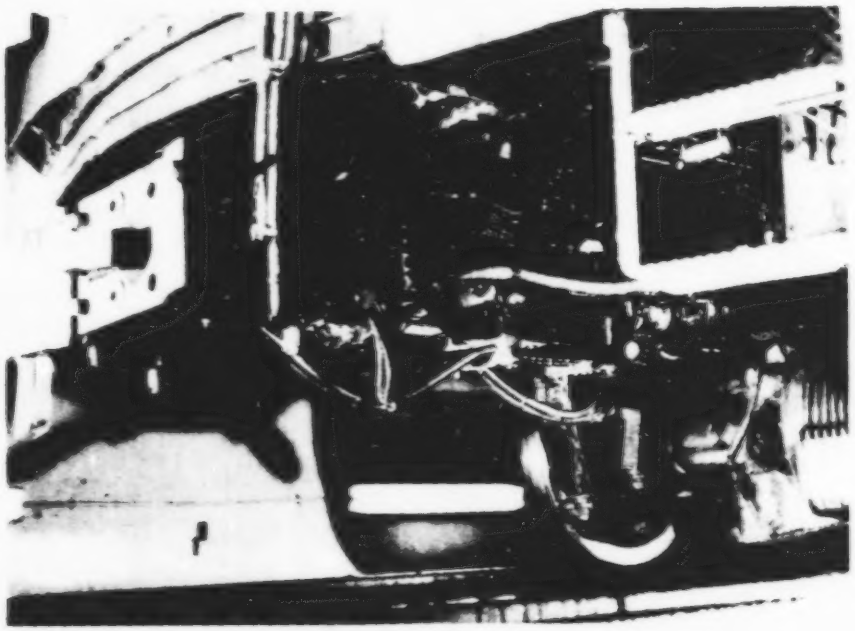
C/ Layout of Robots under a TTC Railcar



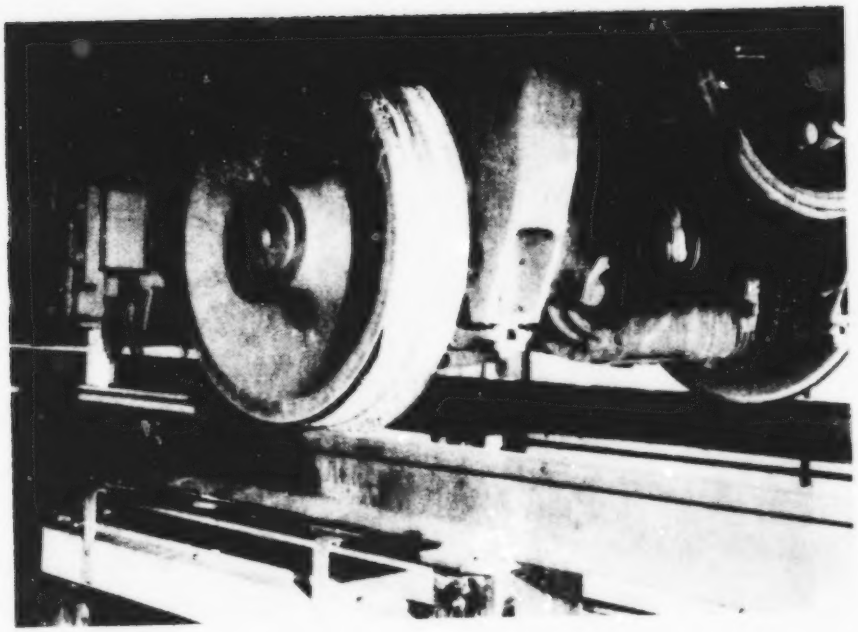
D/ Layout of Central Robot under a TTC Railcar



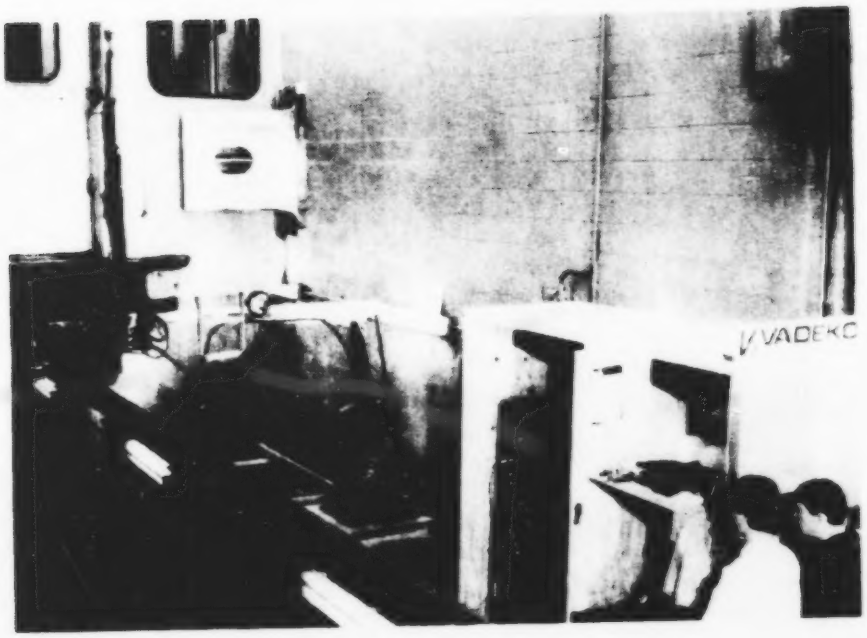
Grease around the collector shoe in the bogie area to be cleaned



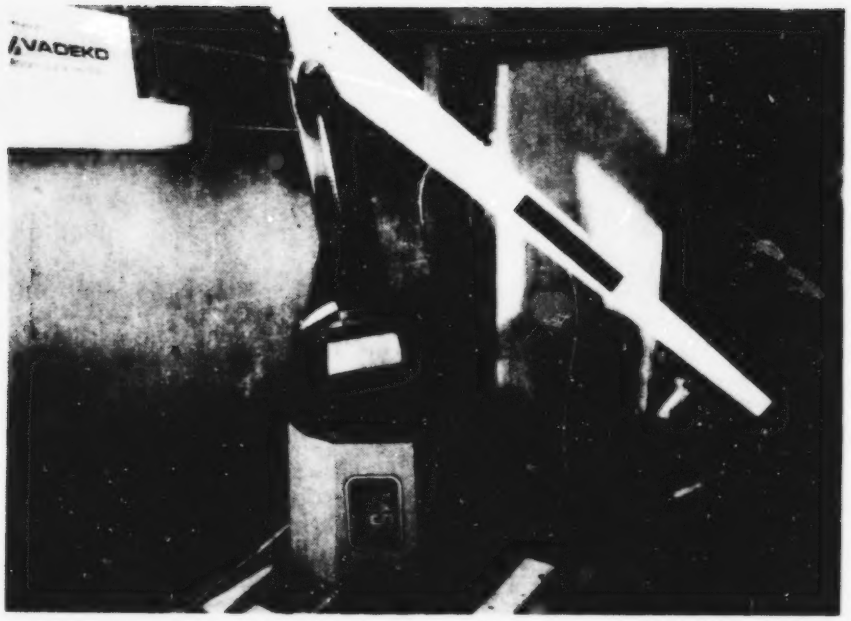
A coupler at the front of the car to be cleaned



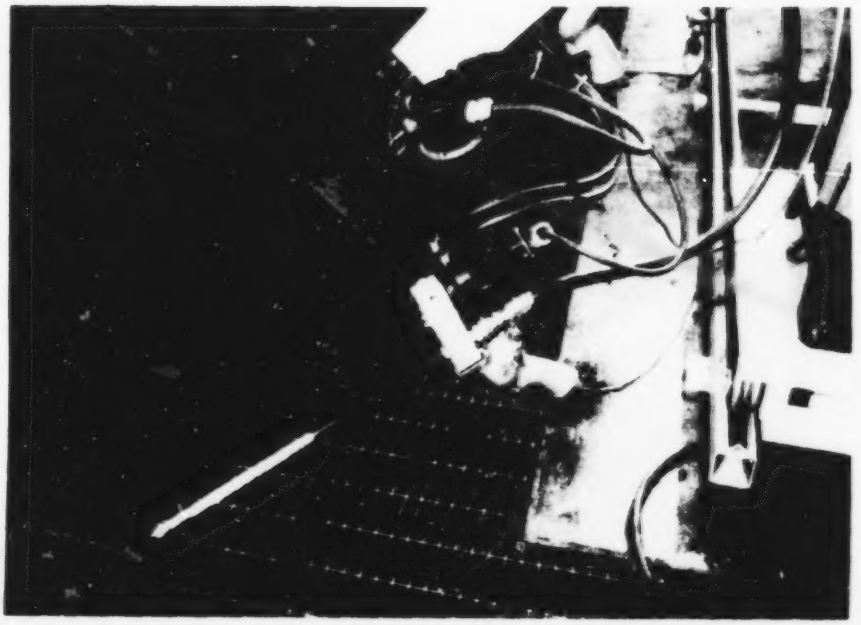
The back of a bogie before cleaning



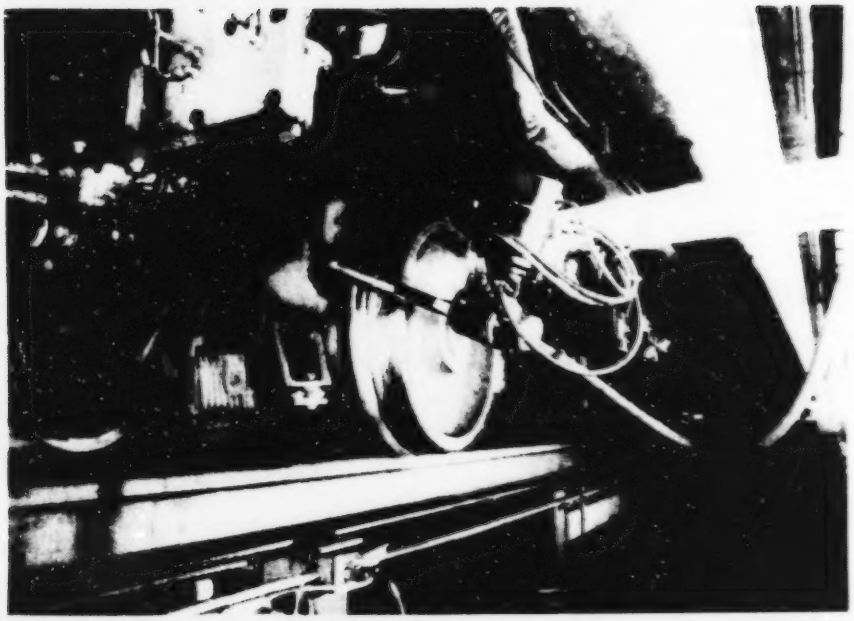
The cleaning system set up for a demonstration



The DeVilbiss TR-450 robot

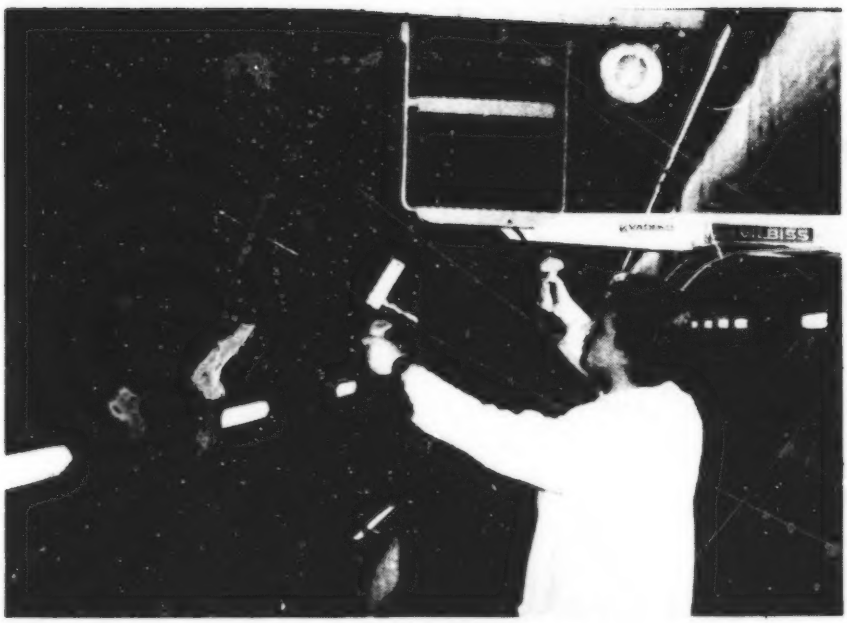


The end of the robot arm set up

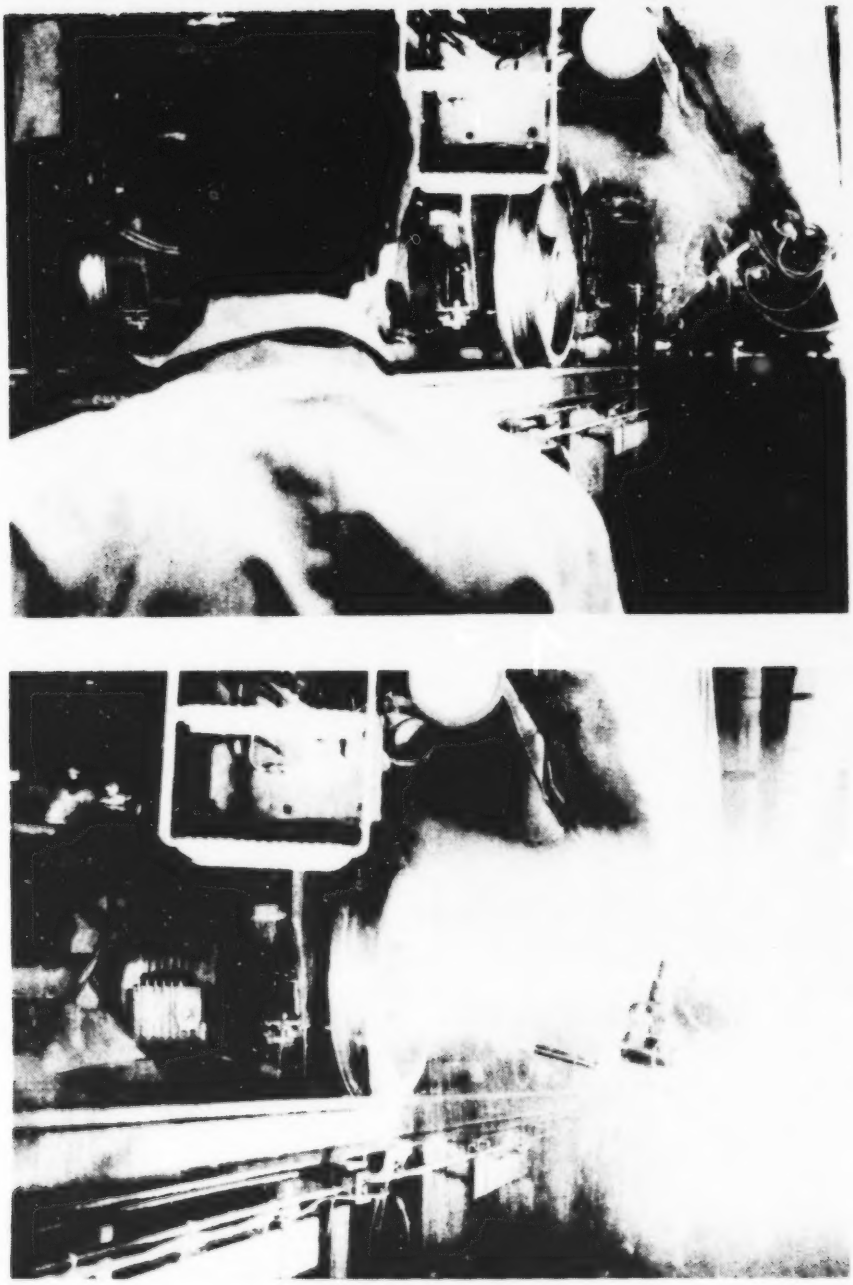


The robot in position for cleaning

The auxiliary controls and teaching pendant



"Teaching" the robot its cleaning moves



The cleaning process